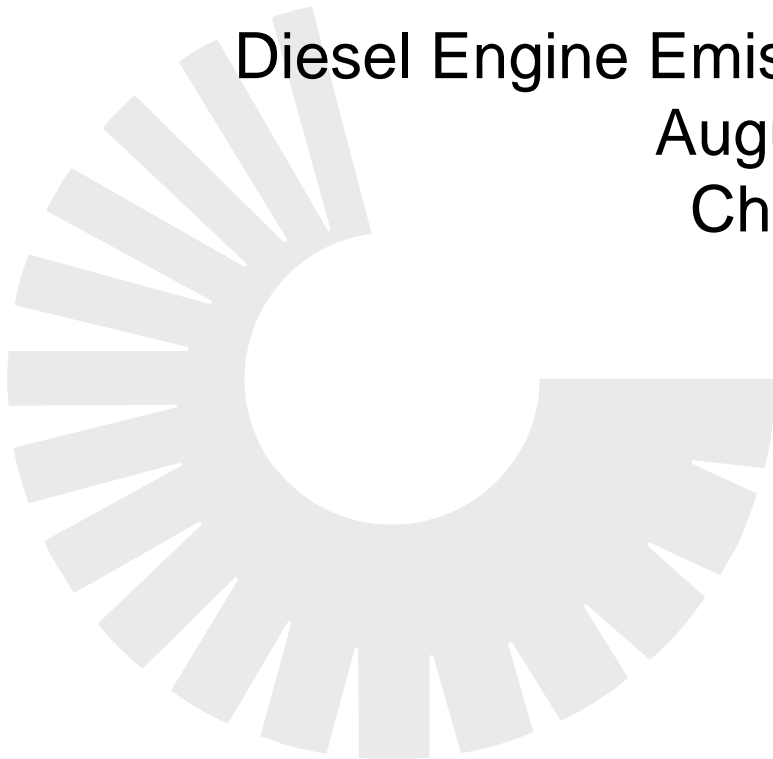


# Cost-Effective Fabrication Routes for the Production of Quantum Well Type Structures and Recovery of Waste Heat from Heavy Duty Trucks

***Rhonda Willigan***

United Technologies Research Center

Diesel Engine Emissions Reduction Conference  
August 25th, 2005  
Chicago, Illinois



[www.utrc.utc.com](http://www.utrc.utc.com)

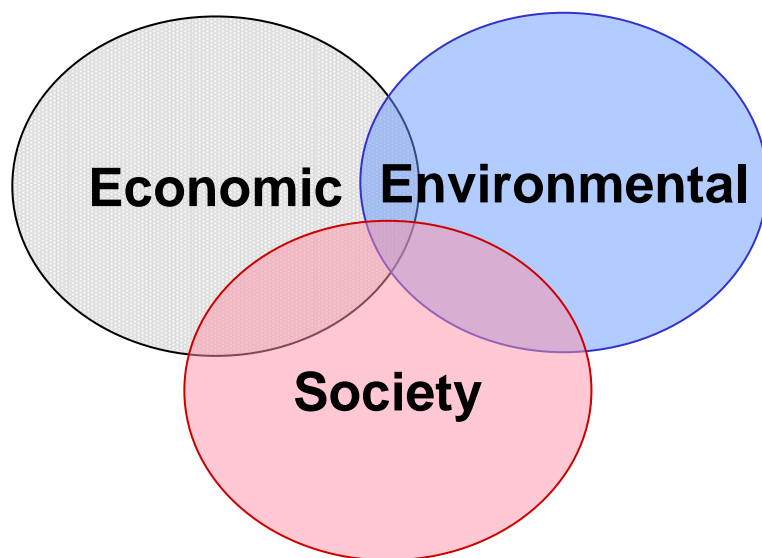
# Outline

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- Motivation for Waste Heat Recovery (WHR)
- Motivation for Waste Heat Recovery from Diesel Engines
- Caterpillar's More Electric Research Truck Platform
- Thermoelectric (TE) Technology
- DOE UTRC-led program for TE-based WHR from Diesel Engines
  - Program Objectives
  - Phase I Results / Phase II Plan

# Motivation for Waste Heat Recovery

*Today's pressure to increase fuel economy & reduce emissions is 3-fold*



- Decreasing fuel supply
- Rising fuel prices
- More stringent emissions regulations
- Truck idling restricted to certain locations
- Increased population / vehicle registration
- Driver Comfort
- Increased demand for auxiliary power

## ***DOE EERE / FCVT Mission:***

Develop more energy-efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum

# Motivation for Waste Heat Recovery from Diesel Engines

## *Could Diesel Play a Future Role in Hybrid Car Designs?*

### (+ / Pros)

- **Diesel fuel has a higher energy content than gasoline**
- **Diesel performance is better than gasoline (30% more efficient)**
- **Vehicles running on diesel put less global warming pollution in the air**

→ *Better Fuel Economy & Less CO<sub>2</sub>*

### (- / Cons)

- **Lower exhaust temperatures**
- **Greater particulates**
- **Higher NOx**

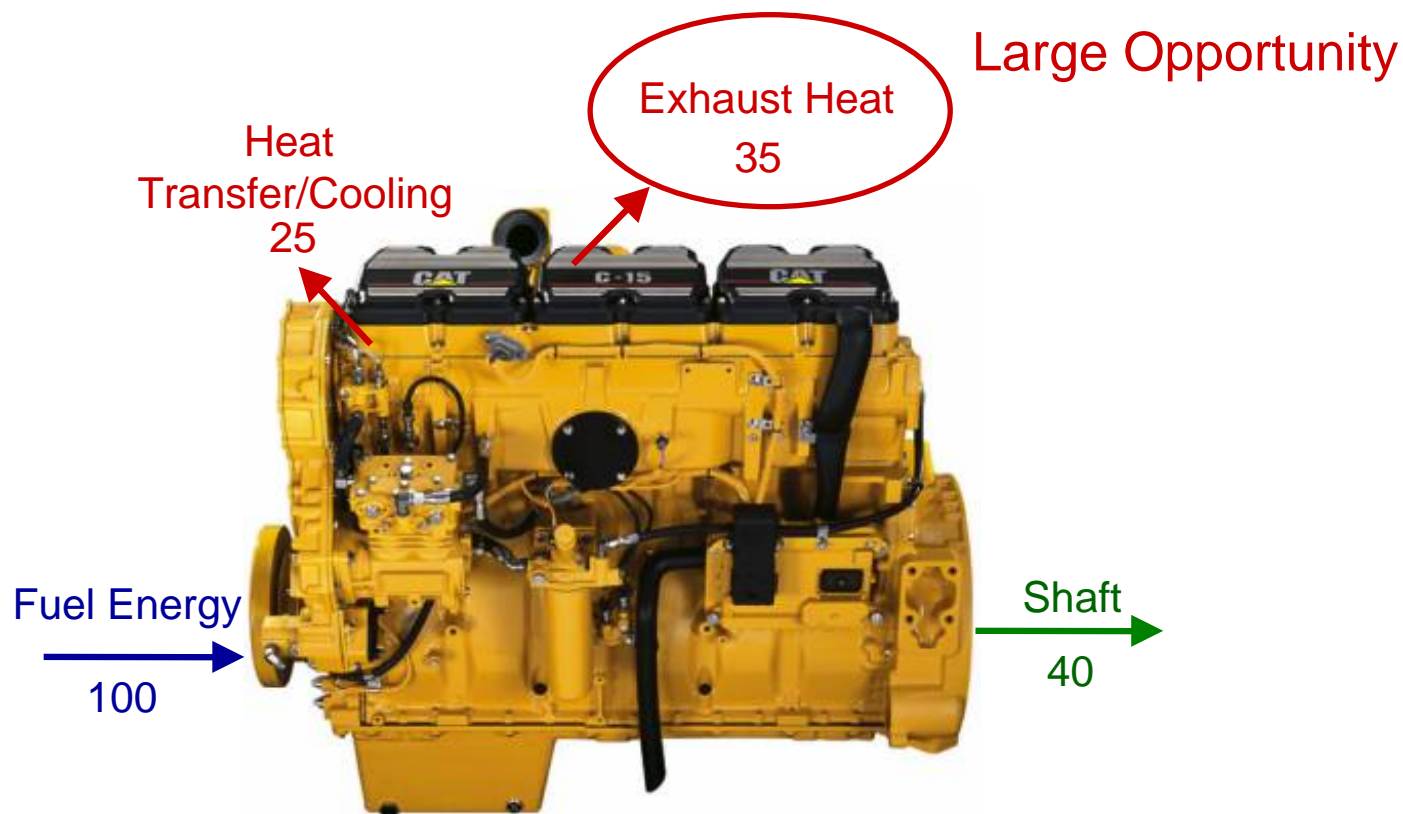
*“Full hybrid-electric diesel cars offer the maximum improvement in fuel economy as well as the greatest reduction in heat-trapping emissions”*

*..... The Diesel Dilemma: Diesel's Role in The Race for Clean Cars*



# Motivation for Waste Heat Recovery from Diesel Engines

*Large opportunity to improve fuel economy and engine efficiency*



Class 8 Truck Engine Energy Audit

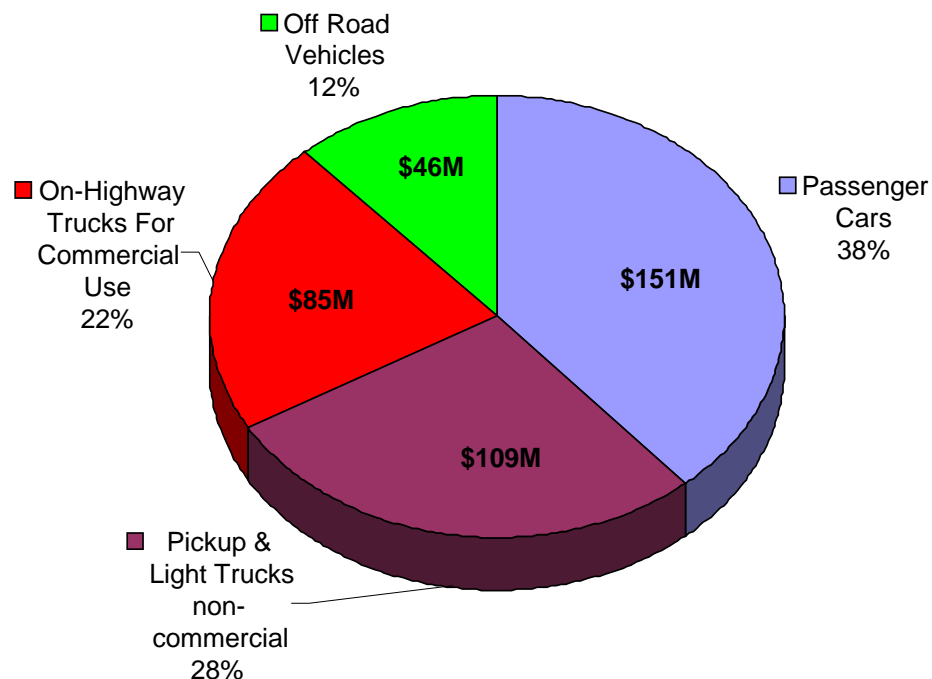
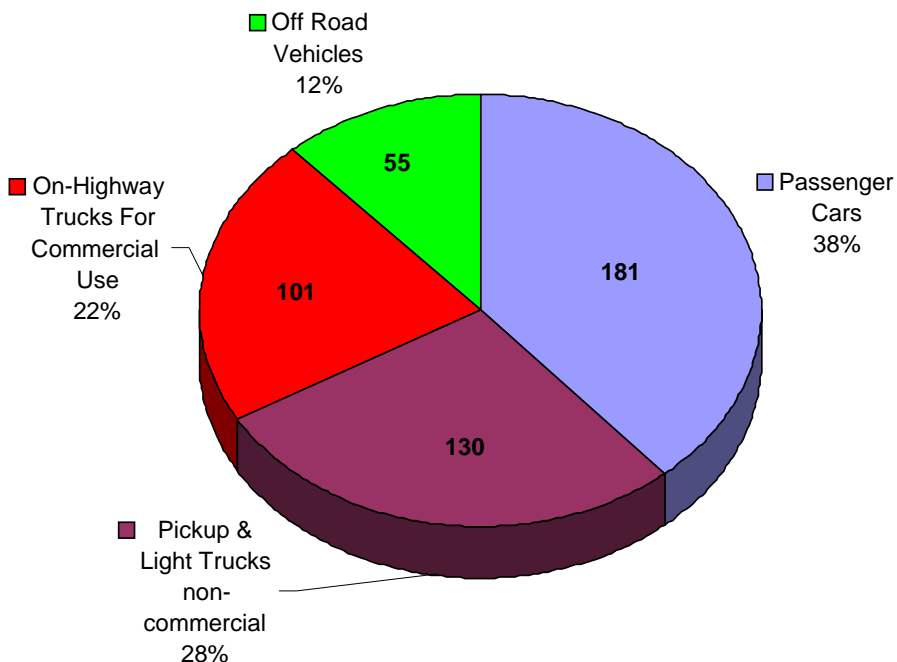
# Motivation for Waste Heat Recovery from Diesel Engines

*Large opportunity to improve fuel economy with early payback*

## Daily Fuel Consumption and Potential Opportunity

**Million Gallons per day**

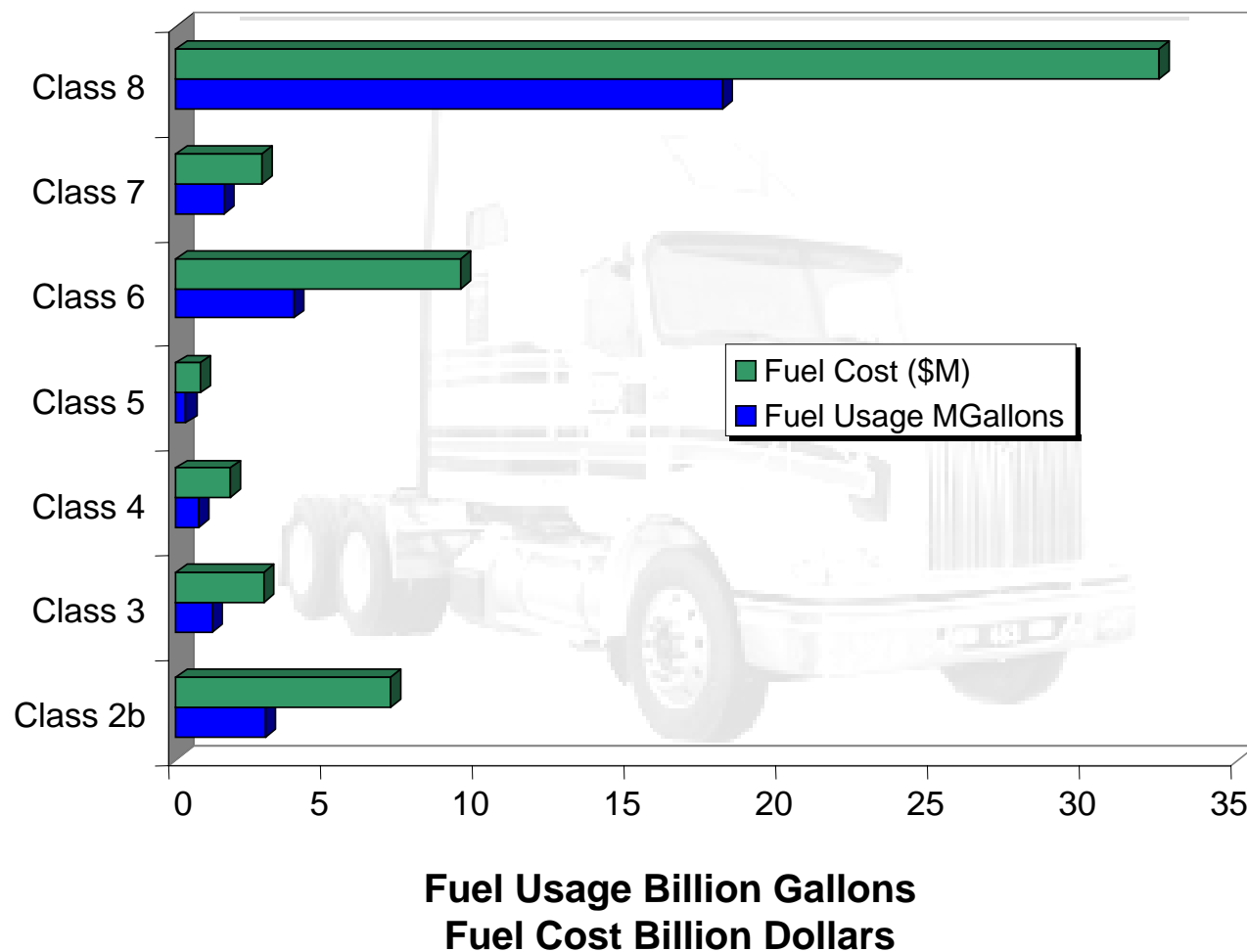
**\$M per day**



**35% waste heat amounts to**

# Motivation for Waste Heat Recovery from Diesel Engines

*Class-8 diesel trucks represent significant portion of fuel consumed*



# Truck Electrification

*Overall better utilization of electrical energy*

## Technical Objectives :

- **Replace gear or belt-driven accessories (pumps, fans, compressors) with electrical accessories**
- **Decouple mechanical loads from the engine**
- **Match power demand to real time need**
- **Enable use of alternative power sources**
- **Technologies must be: Cost-effective, Reliable, and Durable**

## Results if Achieved:

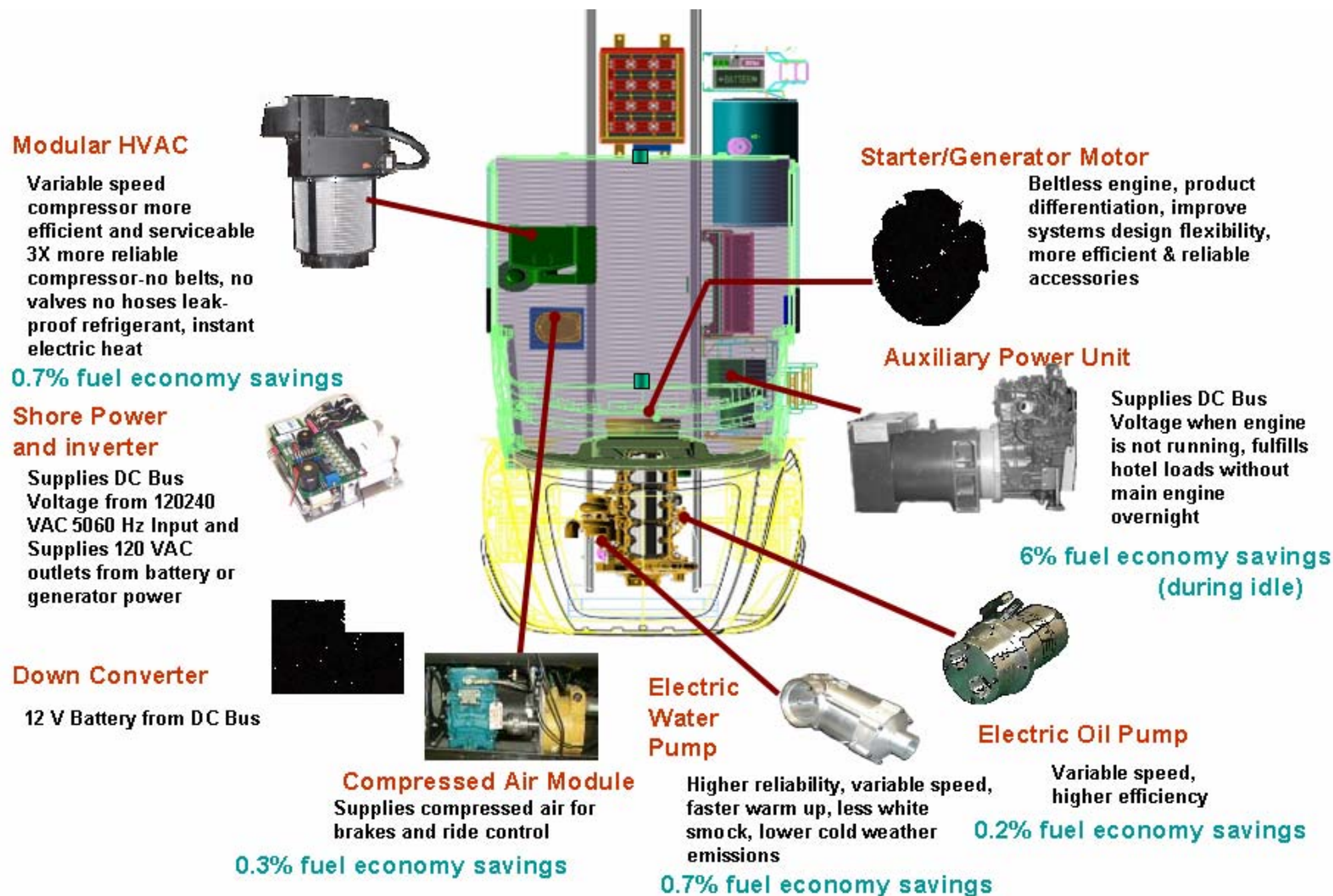
- **Electrical components can be:**
  - **Operated at individual, optimal speeds**
  - **Reduced to smaller size, and**
  - **Ideally located**
- **Cooling loads can be reduced**
- **Engine can be redesigned to reduce drag**



***\*DOE WHR Program is equally important, and synergistic, to DOE's More Electric Truck & Essential Power System (EPS) Program in achieving the overall fuel savings goal of 1 billion gallons per year***

# Caterpillar's More Electric Research Truck Platform

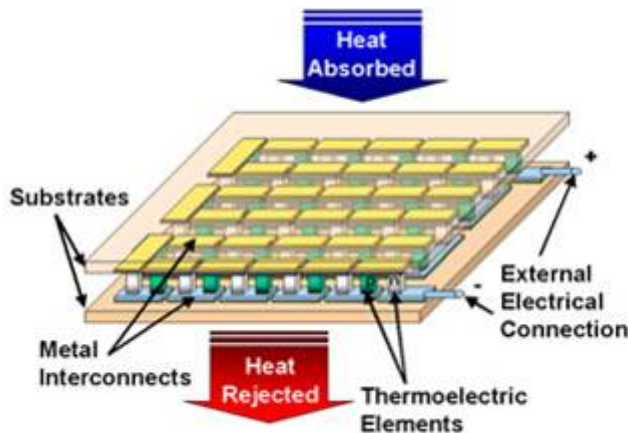
## *Effective "Decoupling" of Essential Power Systems from Engine Gear-Drive*



# *Thermoelectrics* for Engine Efficiency Improvement

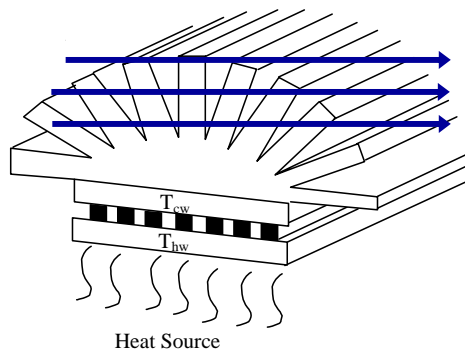
## *Basic Principles....and Challenges Associated with TE Waste Heat Recovery*

### Basic Principles



- Voltage resulting from an imposed temperature difference across two dissimilar materials, usually semiconductors.
- Material used must simultaneously possess high electrical conductivity and low thermal conductivity.
- Dissimilar materials are connected electrically in series and thermally in parallel.

### Challenges



- Heat transfer in and out of the TE devices...within allowable backpressure to engine
- Added weight to system due to integration of TEG
- Large, steady  $\Delta T$  without running fans/pumps
- High ZT (high efficiency) materials across existing  $\Delta T$

# DOE Waste Heat Recovery & Utilization Program

## Program Overview

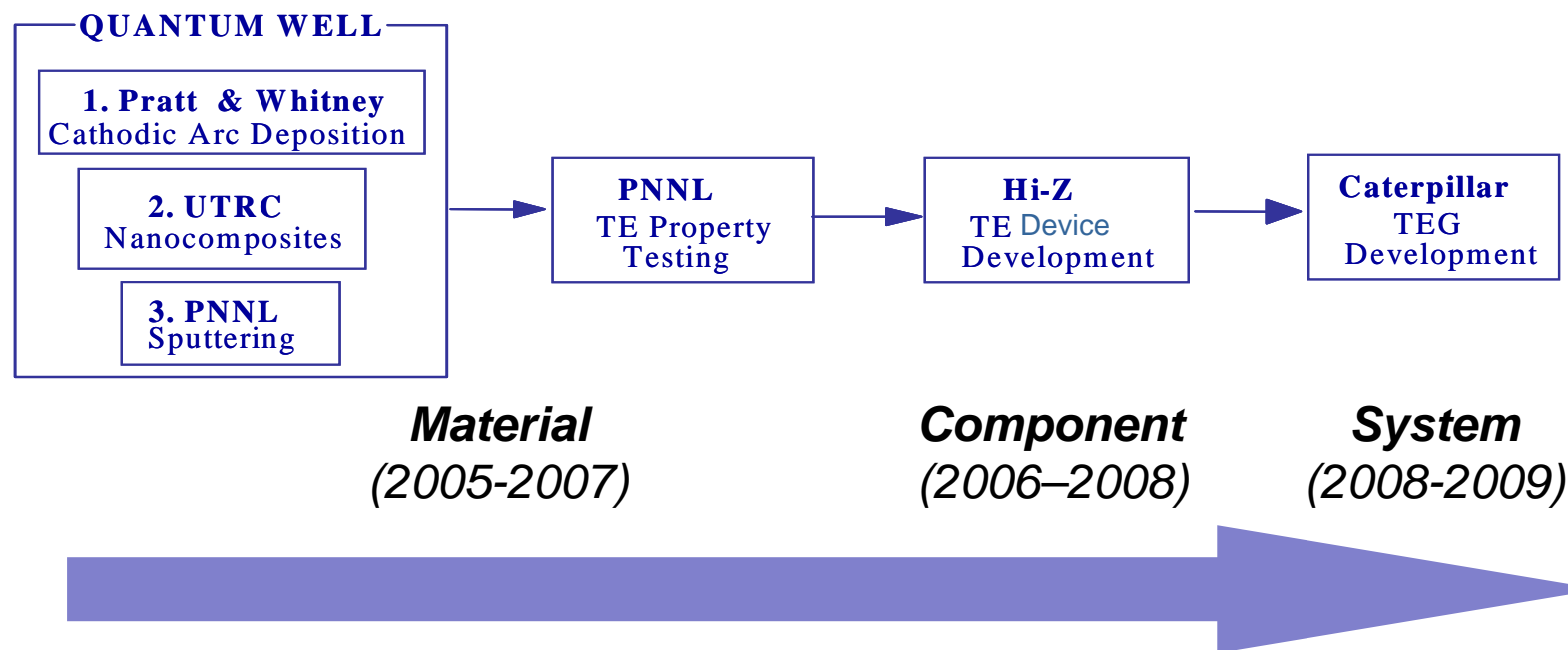
- 4-phase, 25% cost-shared R&D program sponsored by the U.S. Department of Energy, National Energy Technologies Laboratory.
- Program goal: Improve the engine efficiency of a heavy-duty, on-highway truck by 10% (*from 40% to 44%*), thus fuel efficiency by 9%



- DOE Program Manager John Fairbanks and DOE Project Manager Ralph Nine

# Program Overview

- Develop a cost-effective fabrication route for the production of quantum well (QW)-type TE materials, enabling the commercialization of high-efficiency TE modules.
- Demonstrate technology in the form of an integrated prototype TE generator on a More Electric Truck (MET) Class 8 heavy duty truck.
  - Deliver a viable commercialization path to the on-highway truck industry.



# UTC Motivation

*Many UTC Applications Exist for TE Cooling, Heating and Power Generation*

*UTC Fuel Cells*



**Waste Heat Recovery  
from SOFC**

*Pratt & Whitney*

**Electrified Aircraft  
Engine**



*Hamilton Sundstrand*

**Personal Comfort  
(Cooling/Heating)**



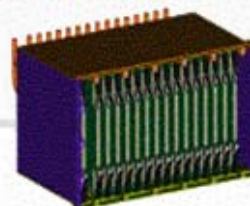
*Carrier*



**Supermarket  
Display Case**

*Hamilton Sundstrand*

**Cooled Power  
Electronics**



*UTC Power*

**Small Auxiliary  
Residential  
Power**



# Hi-Z's Experience in Waste Heat Recovery from Engines

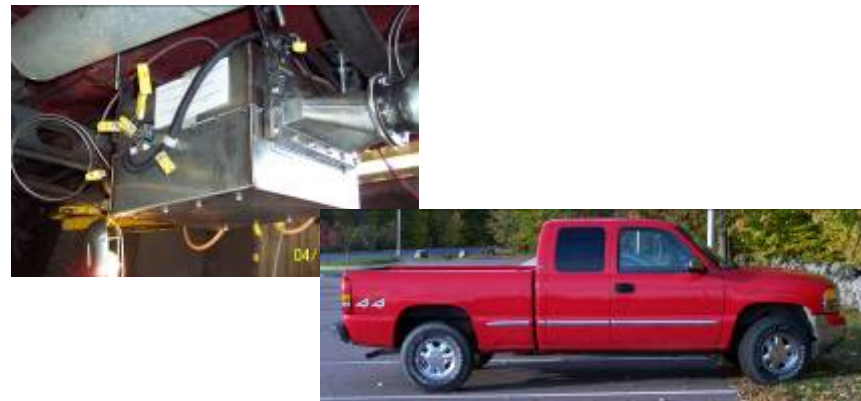
## 1kWatt TEG for Heavy-Duty Trucks

- DOE funded program
- Utilizing  $\text{Bi}_2\text{Te}_3$  TE devices
- Tested equivalent of 500,000 miles in test bed mounted under a PACCAR truck



## 300 Watt TEG for Light-Duty Trucks

- In conjunction with Clarkson University
- Utilizing  $\text{Bi}_2\text{Te}_3$  TE devices
- Tested in a Sierra Pickup Truck



## 200 Watt TEG for a Hybrid Truck

- In conjunction with to Ohio State
- Utilizing  $\text{Bi}_2\text{Te}_3$  TE devices



# DOE Waste Heat Recovery & Utilization Program

## *Phase I Objectives*

### **Perform a techno-economic study for the integration of a QW-based thermoelectric generator (TEG) into Class 8 trucks for the purpose of waste heat recovery**

- Determine application-specific conditions
- Evaluate, under these application-specific conditions, expected power output using targeted TE materials.
- Define market acceptance criteria
- Identify viable TEG concepts
- Downselect to most promising TEG concept and apply best design
- Establish maximum acceptable cost/kW targets
- Quantify/Compare costs of different fabrication routes
- Quantify total TEG cost and compare to system level requirements

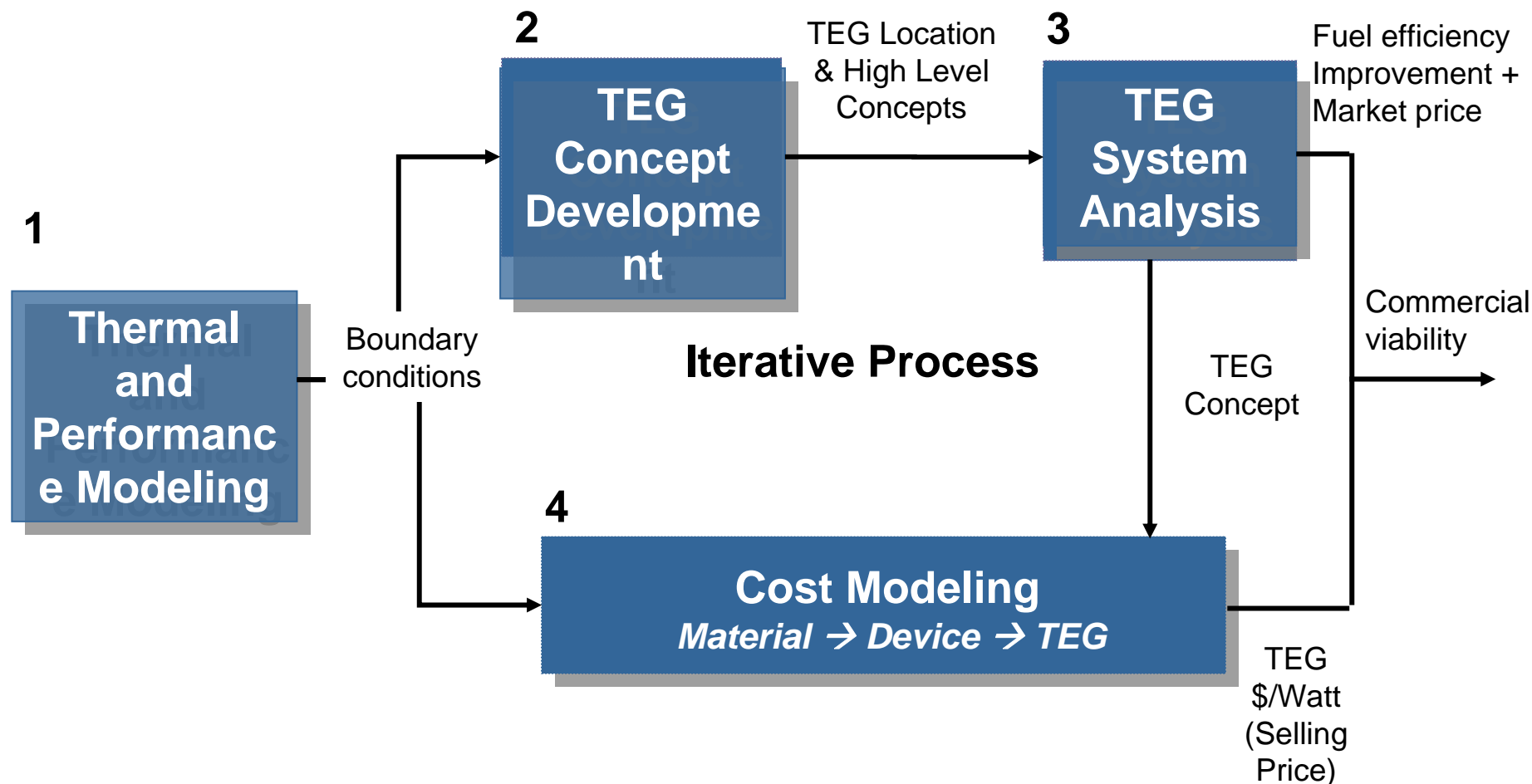
### **Success Criteria**

- Projected cost and performance metrics meet or exceed system level requirements



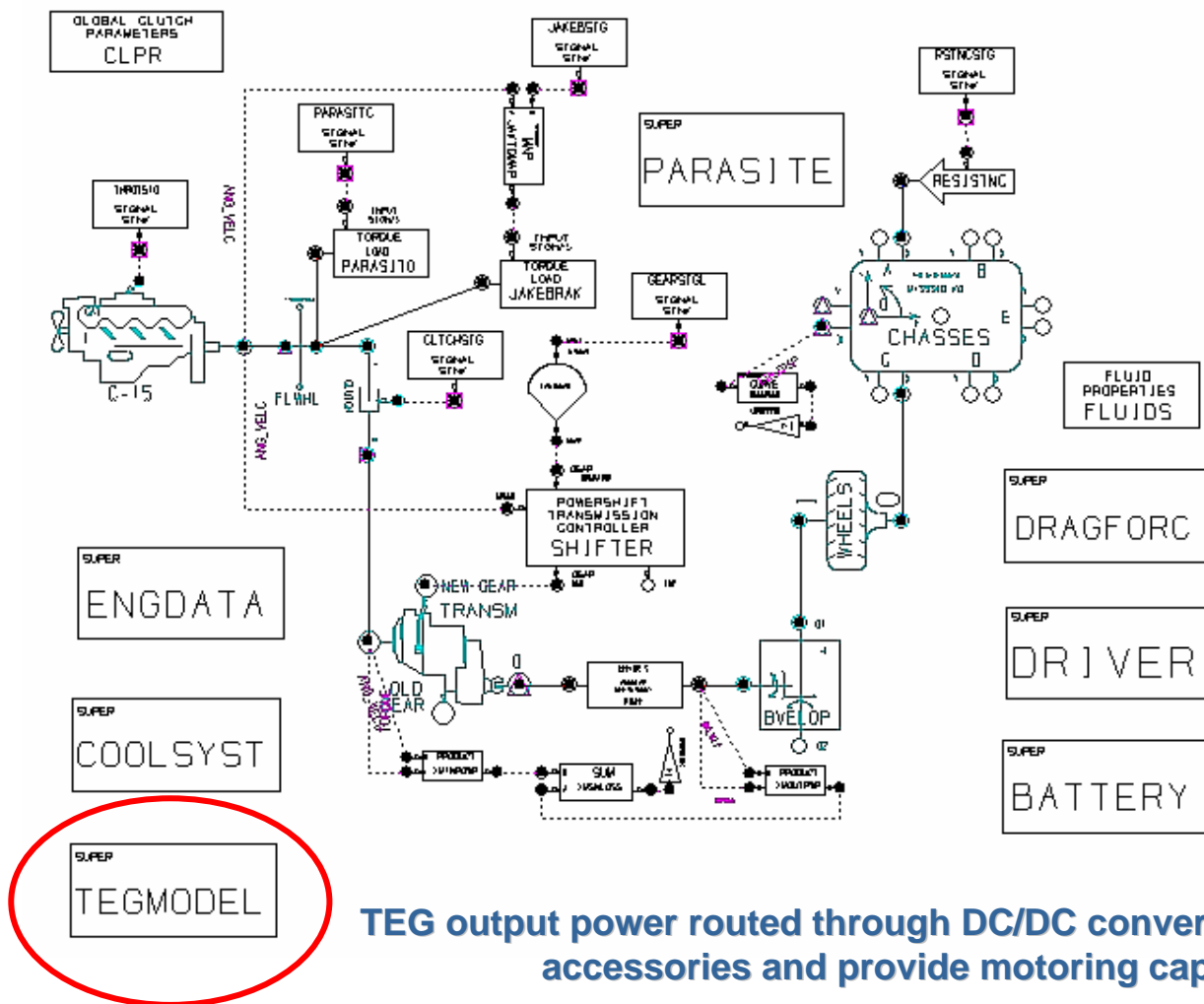
# DOE Waste Heat Recovery & Utilization Program

## Phase I Approach



# Main View of Dynasty Truck Model

## Complete system analysis



### Model Inputs

Desired Speed & Route Conditions

### Model Outputs

Engine, Cooling System, & Electrical System Performance (Temps, Speeds, Loads, Powers, Flow Rates, Voltages, Etc.)

Fuel Efficiency Improvement

# DOE Waste Heat Recovery & Utilization Program

## Phase I Results

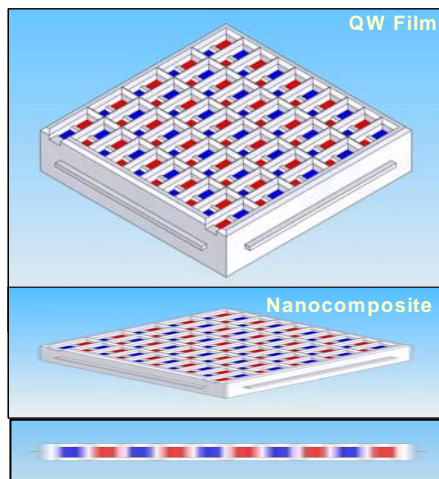
### System Analysis

- 5 – 12 kWatt thermoelectric generator (TEG) using liquid cooling on cold side chosen for highest power output and lightest weight.
- Preliminary TEG concept, combined with Caterpillar's More Electric Truck Platform, gives a projected fuel efficiency improvement of 4 - 4.5%. Critical customer requirements determined at 2 – 9%.

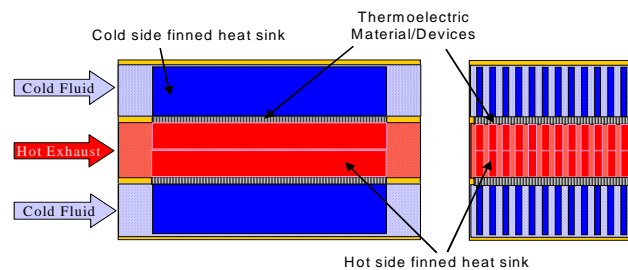
### Cost Analysis

- QW-based thermoelectric generator projected to sell at \$0.51/watt compared to the maximum market acceptable price of \$0.46/watt
- TE devices and generator components contribute equally to total fabrication cost.
- 2-year payback assumed

### TE Device Design



### TE Heat Exchanger Design



### TE Generator Design



# DOE Waste Heat Recovery & Utilization Program

## *Phase II Plan*

- ❖ Demonstrate cost-effective fabrication approaches for high efficiency TE materials
- ❖ Determine thermal stability of the fabricated QW- type structures
- ❖ Identify and overcome key risks associated with the integration of thermoelectric materials into a subsystem level device
- ❖ Define requirements and design the TE device – TEG interface
- ❖ Develop a technical path for fabricating a prototype subsystem level heat management unit for concept generation



# Summary

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- Waste heat recovery is a large opportunity for Off and On-highway truck market
- Caterpillar has an available platform for immediate demonstration of the technology
- A conservative approach was taken at system level (e.g, realistic allowable backpressures and drive cycles) to project the fuel efficiency improvement, which meets customer requirements.
- Cost models project a selling price equal to market value ( $\sim \$0.5/\text{Watt}$ ), making the technology commercially viable. Payback period estimated at be 2 years.